

# **Role of Tidal Forcing in Determining the Internal Wave Spectrum in the Littoral Ocean**

Jeffrey D. Paduan

Department of Oceanography, Code OC/Pd

Naval Postgraduate School

Monterey, CA 93943

phone: (831) 656-3350; fax: (831) 656-2712; email: [paduan@nps.navy.mil](mailto:paduan@nps.navy.mil)

Leslie K. Rosenfeld

Department of Oceanography, Code OC/Ro

Naval Postgraduate School

Monterey, CA 93943

phone: (831) 656-3253; fax: (831) 656-2712; email: [lkrosenf@nps.navy.mil](mailto:lkrosenf@nps.navy.mil)

Document #: N00014-99WR-30021

<http://www.oc.nps.navy.mil/~radlab/LIWI>

## **LONG-TERM GOALS**

The long-range goals of this project are to understand the environmental factors that define the level of internal wave activity in the littoral oceans and to develop re-locatable models capable of predicting these levels.

## **OBJECTIVES**

This project seeks to document the nature of internal wave spectra in the littoral ocean environment around Monterey Bay using existing moored velocity time series and simulated coastal time series produced by a three-dimensional, primitive equation numerical model with realistic bathymetry forced by tidal-period sea level oscillations. Project goals include the desire to establish a practical and relocatable modeling framework that can be used to predict littoral internal wave statistics for any other coastal region similarly dominated by baroclinic processes.

## **APPROACH**

This project builds on the works of Petruncio (1996) and Petruncio et al. (1998), which describe the strong, bottom-intensified internal tide in Monterey Submarine Canyon. A primitive equation numerical model, the Princeton Ocean Model (POM), is being utilized in a coastal setting where detailed bottom topography and in situ current observations are available. POM is initialized with high resolution side-scan bathymetry and observed stratification over a 113 km x 130 km domain with 1 km resolution and 30 levels. It is forced with tidally varying sea level at the offshore boundary. A modified version of POM, produced by Dr. Le-Ngoc Ly, is also being tested on the Monterey Bay domain. The primary difference is that Dr. Ly's model is being forced around all three open boundaries with the eight largest tidal constituents. The two model versions will be merged,

eventually, to produce the most realistic numerical laboratory for internal tidal studies of the Monterey Bay region.

## **WORK COMPLETED**

Efforts this year focused on extending the idealized model domain of Petruncio et al. (1999) to include the realistic bathymetry of Monterey Submarine Canyon. Initial runs have been completed using the offshore-only boundary forcing of those earlier studies. In addition, Dr. Ly has completed testing of the all-boundary, multi-constituent tidal forcing of his model, which has highlighted the sensitivity of the barotropic tidal forcing to the boundary specifications in these types of model domains.

## **RESULTS**

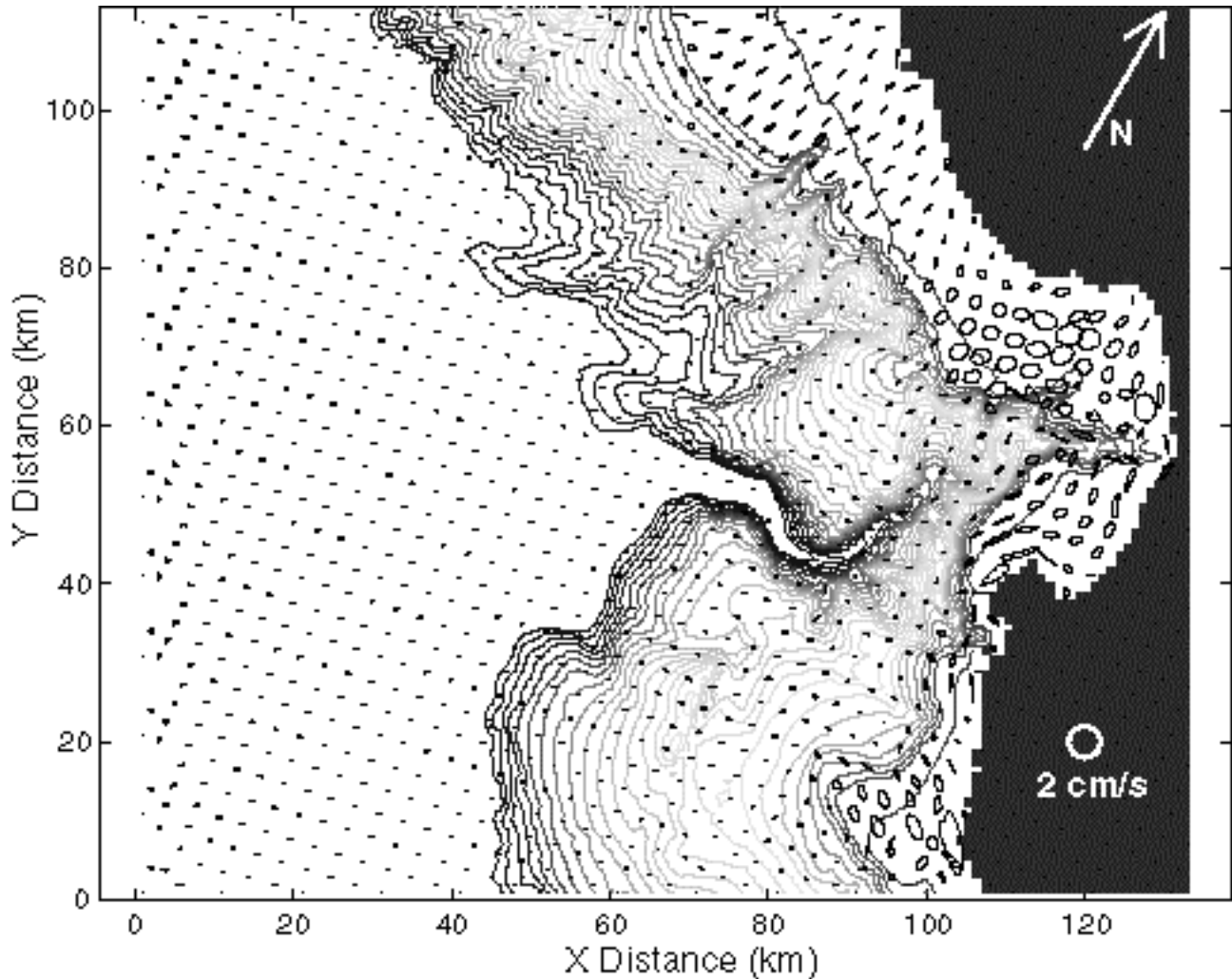
This project has continued to show the clear influence of bottom topography on the propagation and amplification of internal waves of tidal period. Observations and model results were presented at the 'Aha Huliko'a Hawaiian Winter Workshop in January 1999, which was devoted to modeling of internal waves. Several project results were published in the proceedings paper of Rosenfeld et al. (1999).

Tidal simulations using POM were run for 10 days using M2 sea level forcing at the offshore open boundary. Radiation boundary conditions were applied at the northern and southern boundaries, while a sponge condition was applied to baroclinic velocities on the offshore boundary as described by Petruncio et al. (1999). Results of this experiment are shown in Figures 1 and 2 for the barotropic forcing and baroclinic response, respectively. In this case, the barotropic current forcing produced by the offshore sea level fluctuations is quite reasonable. Cross-shelf, depth-averaged velocities are  $\sim 1$  cm/sec as predicted from global tidal models. In the shallower areas over the continental shelf, depth-averaged currents reach a maximum  $\sim 4$  cm/sec with clear directional correlation with bottom topographic features.

The resulting baroclinic flow along the bottom shown in Figure 2 is even more strongly tied to the topography. The maximum currents exceed 12 cm/sec and are found within the axis of the Monterey Submarine Canyon, similar to the observations of Petruncio et al. (1998). The near-bottom hodographs are much less elliptical than those of the depth-averaged currents, which suggests asymmetric flows for the upcanyon and downcanyon portions of the tidal cycle and/or significant nonlinear transfer to high-order tidal harmonics. Evidence for both effects was recorded by the ADCP measurements in the canyon axis reported by Rosenfeld et al. (1999).

Although most of the barotropic-to-baroclinic energy conversion is expected to derive from the weak cross-shore component of the depth-averaged tidal currents, it may also be important to include along-shore forcing given the complicated geometry of the bottom topography. To accomplish this, forcing along all three open boundaries of the model domain is required. This has been accomplished with a larger-scale POM implementation off British Columbia by Cummins and Oey (1997). In each case, the resulting depth-averaged forcing must be carefully inspected for excessively large currents, which can result from the slightest mismatch in phase along the boundaries. We have begun to test the all-boundary forcing of the Monterey Bay domain using the model developed by L. Ly. The modeled sea level over thirty days produced using all-boundary forcing and eight tidal constituents is shown in

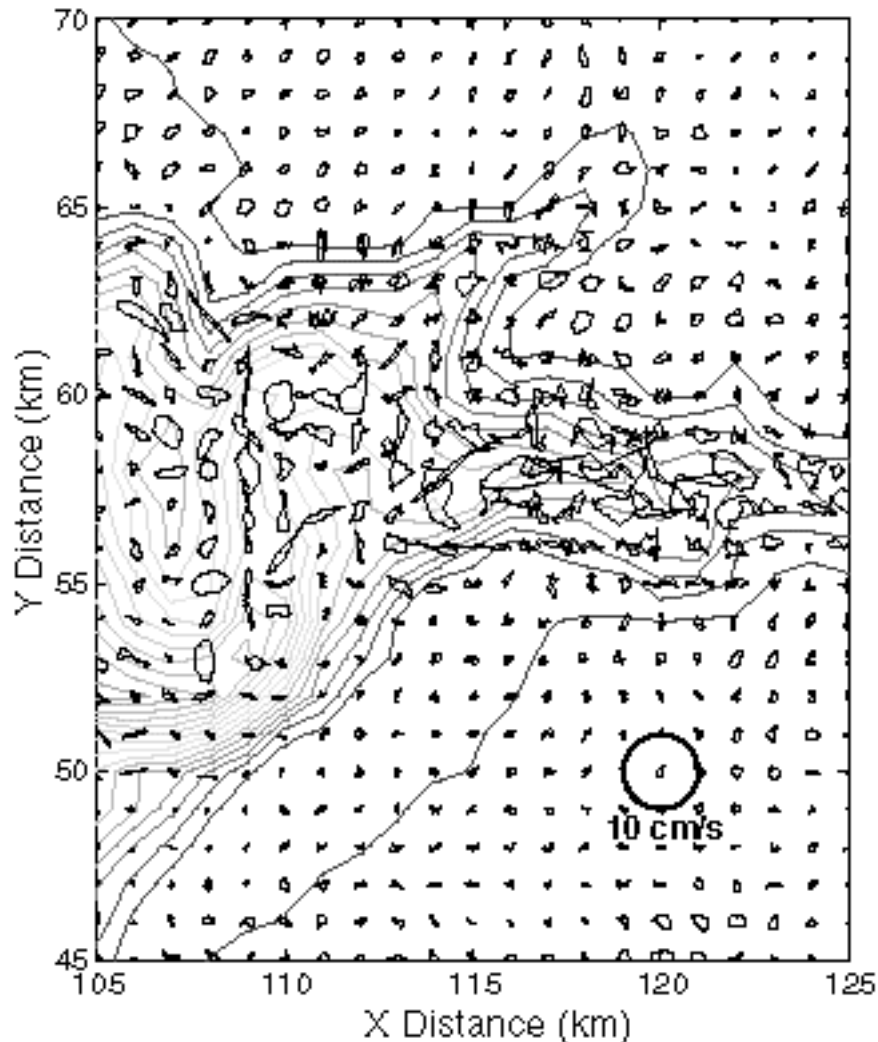
Figure 3 along with coastal observations from the Monterey Bay portion of the domain. The agreement is very good. Not shown, however, are regions along the coast further north for which the modeled sea level fluctuations are unrealistically high, as well as small regions within the model interior for which the modeled depth-averaged currents are also too high. Additional tuning of the open boundary conditions along with a revised bottom dissipation formulation are being investigated to address these problems.



**Figure 1.** *Depth-averaged current hodographs over a semidiurnal tidal cycle on day 10 of the POM simulation of Monterey Bay. Every 5<sup>th</sup> model grid point is shown. The contour interval is 100 m and the largest speeds are ~4 cm/sec over the continental shelf.*

## IMPACT/APPLICATIONS

The likely impact of this project will be a change in the way predictions of internal wave energy are made for the coastal oceans with a much greater role to be played by limited-area, high-resolution numerical model simulations.



**Figure 2.** *Bottom current hodographs over a semidiurnal tidal cycle on day 10 of the POM simulation. Every grid point is shown for the Monterey Bay portion of the model domain. The contour interval is 100 m and the largest speeds are ~12 cm/sec in the axis of the canyon.*

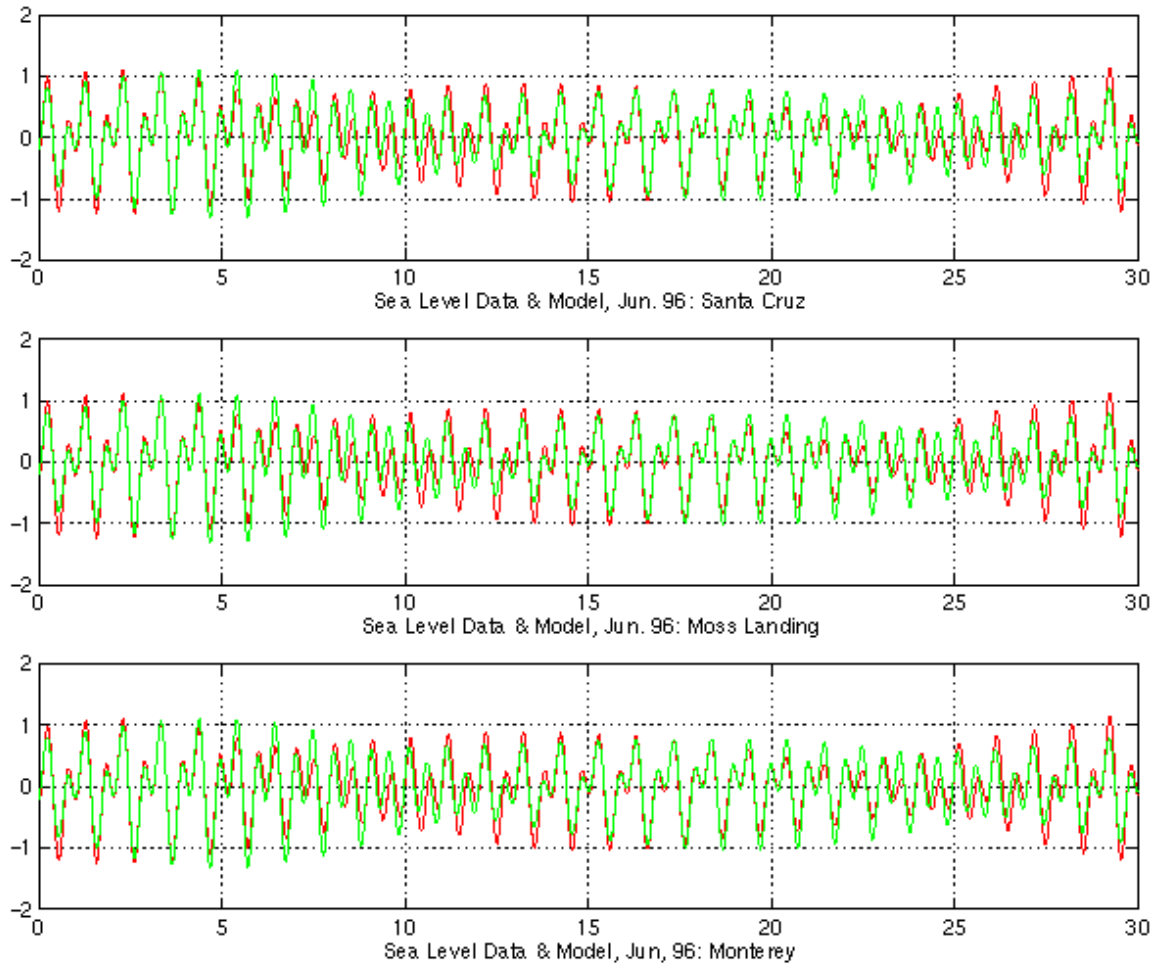
## TRANSITIONS

Our preliminary results have motivated other research groups to investigate the role of submarine canyons in generating strong internal tides and the ability of primitive equation models to simulate this process. The obvious transition targets for this technology are the modeling groups within the Naval Oceanographic Office responsible for assessing environmental parameters for strategic portions of the coastal oceans.

## RELATED PROJECTS

This project is a component of ONR's Littoral Internal Wave Experiment (LIWI). Of direct importance to this project is the field program of Leslie Rosenfeld, Mike Gregg, and Eric Kunze, which is jointly sponsored by LIWI and NSF and is designed to observe turbulent mixing in and around Monterey Submarine Canyon driven by the internal tide. Similarly, the very large field program

funded by NSF to study internal tides around Oahu (the Hawaiian Ocean Mixing Experiment, HOME) represents an expanded application of the techniques being studied here. This project was greatly aided by the dissertation work of Brazilian Ph.D. student José Eduardo Goncalves from the University of São Paulo, who was partially supported by this project during an extended visit to the Naval Postgraduate School.



**Figure 3. Observed (red) and modeled (green) sea level for June 1996 at Santa Cruz, Moss Landing, and Monterey for the eight-constituent barotropic tidal model of L. Ly.**

Our collaborations on moored observations, HF radar measurements, satellite imagery, and numerical modeling in the Monterey Bay region also fall under the auspices of the National Ocean Partnership Program (NOPP). The Monterey component of the Program, entitled an Innovative Coastal-Ocean Observing Network (ICON), encompasses many of the data sets and investigators affiliated with this project. J. Paduan serves as principal investigator for ICON (see <http://www.oc.nps.navy.mil/~icon/>).

## REFERENCES

Cummins, P.F., and L.-Y. Oey, 1997: Simulation of barotropic and baroclinic tides off northern British Columbia. *J. Phys. Oceanogr.*, **27**, 762-781.

Petruncio, E.T., 1996: Observations and modeling of the internal tide in a submarine canyon. Ph.D. dissertation, Dept. of Oceanography, Naval Postgraduate School, 181 pp.

Petruncio, E.T., L.K. Rosenfeld, and J.D. Paduan, 1998: Observations of the internal tide in Monterey Canyon. J. Phys. Oceanogr., **28**. 1873-1903.

Petruncio, E.T., J.D. Paduan, and L.K. Rosenfeld, 1999: Numerical Simulations of the Internal Tide in a Submarine Canyon. J. Phys. Oceanogr., Submitted.

## **PUBLICATIONS**

Rosenfeld, L.K., J.D. Paduan, E.T. Petruncio, J.E. Goncalves, 1999: Numerical Simulations and Observations of the Internal Tide in a Submarine Canyon. Proceedings, 'Aha Huliko'a Hawaiian Winter Workshop., University of Hawaii at Manoa, January 25-29, 8 pp.